

IRC+10216's Innermost Envelope — The eSMA'S View

Hiroko Shinnaga,¹ Ken H. Young,² Remo P. J. Tilanus^{3,4},
 Richard Chamberlin,¹ Mark A. Gurwell,² David Wilner,²
 A. Meredith Hughes,² Hiroshige Yoshida,¹ Ruisheng Peng,¹
 Brian Force,¹ Per Friberg,³ Sandrine Bottinelli,⁵
 Ewine F. van Dishoeck,⁵ Thomas G. Phillips¹

Abstract. We used the Extended Submillimeter Array (eSMA) in its most extended configuration to investigate the innermost circumstellar envelope (CSE) of IRC+10216 where acceleration of gas and dust due to strong stellar radiation is taking place. We imaged the CSE using HCN and other molecular lines with a beam size of $0''.22 \times 0''.46$, deeply into the very inner edge ($\sim 15 R_*$) of the envelope where the expansion velocity is only $\sim 3 \text{ km s}^{-1}$. HCN maser components are spatially resolved for the first time on an astronomical object. We identified two discrete regions in the envelope: a region with a radius of $\leq 15 R_*$, where molecular species have just formed and the gas has begun to be accelerated, and a shell region with a radius of $\sim 23 R_*$. These two regions may have emerged because the size distribution of the dust particles are significantly different in these regions. The position angle of the most copious mass loss direction was found to be $\sim 120 \pm 10$ degrees. In this paper, we summarize some of the highlights of this observational study.

1 Introduction

IRC+10216 is the most studied carbon star. Because of its proximity (distance of 135 pc), it shows a very rich spectrum of molecular and atomic lines particularly at millimeter and submillimeter wavelengths. As such, IRC+10216 is an important target for circumstellar and interstellar chemistry. The carbon star is a red giant that is evolving toward the post asymptotic giant branch (post-AGB) phase. It has a high mass-loss rate of up to $10^{-5} M_\odot \text{ yr}^{-1}$, and is therefore enshrouded by optically thick circumstellar shells.

Hydrogen cyanide (HCN) is one of the most abundant molecular species in the circumstellar envelopes (CSEs) of carbon stars and is known to show maser

¹ California Institute of Technology Submillimeter Observatory, 111 Nowelo St. Hilo HI 96720 U.S.A.

² Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138 U.S.A.

³ Joint Astronomy Centre, 660 North A'ohoku Place, University Park, Hilo HI 96720 U.S.A.

⁴ Netherlands Organization for Scientific Research, P.O. Box 93138, NL-2509 AC The Hague, The Netherlands

⁵ Leiden Observatory, Leiden University, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands

action in various vibrational states. Amazingly, some of the HCN maser lines are in very high energy levels (4000 K or above), far above than the temperature of the photosphere or the dust temperature of the region. This paper reports detections of two lines at such high energy levels.

The Extended Submillimeter Array (eSMA) is a heterogeneous array that combines the signals detected with the eight 6 meter SMA antennas, the CSO 10.4 meter telescope, and the JCMT 15 meter telescope. Including the CSO in the interferometer, one can extend the longest baseline up to ~ 782 meters, which improves the spatial resolution by $\sim 40\%$.

2 Observation and Data Reduction

We observed IRC+10216 in HCN $J = 3 - 2$ transitions in various vibrational states along with other molecular transitions with the eSMA (Bottinelli et al. 2008) on 14 April 2008 (UT). The total bandwidth of ~ 4 GHz (2 GHz from each sideband, i.e., 264.357 – 266.337 GHz and 274.357 – 276.338 GHz) was covered with a frequency resolution of 812.5 kHz. The data were taken under moderate weather conditions with zenith opacities of $\tau \sim 0.15 - 0.18$ measured at 225 GHz. The SMA was configured in its very extended array (maximum baselines to 508 m); the eSMA then covered baselines ranging from 25 to 782 m (~ 20 to 692 k λ or $\sim 0''.2$ to $10''$).

While the continuum emission of IRC+10216 is marginally resolved on the longest baselines, we have performed self-calibration of the visibility phase gains using the continuum, approximated by a point source, as our primary phase calibration step. Flux calibration was achieved by setting the continuum component of IRC+10216 to 1.18 Jy, consistent with well calibrated observations obtained in the SMA compact array in March 2008 whose beam size was about $3''$. Based on the estimated flux of 1.18 Jy for IRC+10216, the calculated flux of the quasar 1058+015 was 2.53 Jy, which was 9% higher than the flux in the calibrator catalog. Since the quasar is linearly polarized by $\sim 25 - 30\%$ at this frequency, the 9% difference may be due to polarization. Note that, by applying self-calibration using the continuum component of IRC+10216, the data taken on the quasar 1058+015 showed that atmospheric decorrelation was eliminated significantly even on long baselines.

3 Results and Discussion

3.1 HCN and Other Molecular Species Detected with the eSMA

Figure 1 (left) shows a part of the spectra that includes a few molecular lines detected with the eSMA. It includes potassium chloride, KCl ($v = 2$), and two HCN transitions in two vibrational states, $v=(1, 1^{\text{lf}}, 0)$ and $(0, 1^{\text{lf}}, 1)$. The energy levels of these transitions are about 5774 K and 4049 K, respectively. Integrated intensity maps of the hot HCN $J = 3 - 2$ emission in the $v=(1, 1^{\text{lf}}, 0)$ is shown in Figure 1 (right). The distribution of the emission is not spatially resolved. The peak of the emission coincides with the stellar position. The radius of the distribution is less than $15 R_*$. The compact distribution supports the scenario that the pumping arises close to the stellar photosphere or at inner

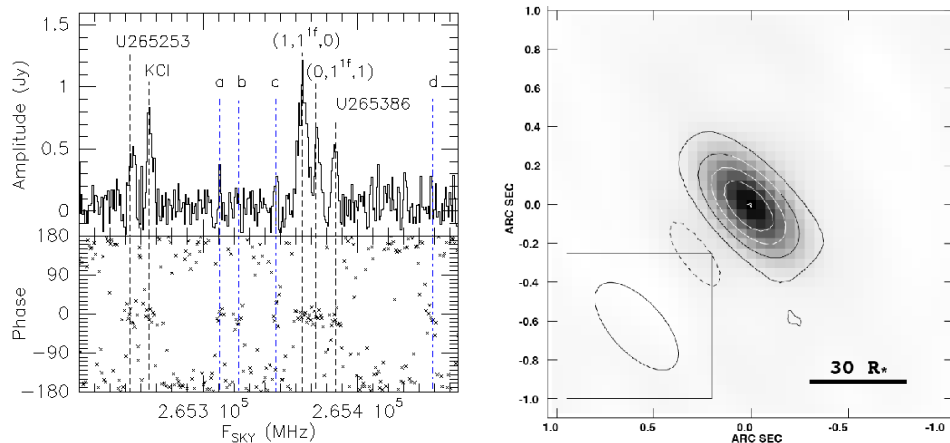


Figure 1. Left: Averaged spectra over all baselines (Shinnaga et al. 2009). Right: Integrated intensity map of HCN $J = 3 - 2$ transitions in the $v = (1, 1^f, 0)$ state (Shinnaga et al. 2009).

edge of the CSE. The lowest expansion velocity estimated among the detected lines is that for the HCN line in the $v=(1, 1^f, 0)$, 3.2 km s^{-1} , which has the highest energy level among detected HCN lines.

Total integrated intensity maps of the HCN $v=(0, 1^{1e}, 0)$ and $v=0$ transitions are shown in Figure 2. In contrast to the map shown in Figure 1 (right), the emission is much more extended. Most of the emission is found within a radius of $1''$, which corresponds to $\sim 60 R_*$. One can find two peaks along the northwest-southeast direction on both maps. The two peaks of both maps are displaced from the stellar position. The position angles ($P.A.$) of the line drawing between two peak components in the $v=(0, 1^{1e}, 0)$ and in the $v=0$ states are 115° and 130° , respectively. The distances of the two peaks of the $v=(0, 1^{1e}, 0)$ map are 90 mas and 300 mas from the central star. The two peaks of $v=0$ map are distributed more or less symmetrically at a distance of 200 mas from the central star.

From the two HCN peaks in Figure 2, we propose that this direction along the two HCN peaks of these transitions may correspond to the direction of most conspicuous mass loss, and that this direction is the equatorial direction of the star. This proposition is consistent with the analysis of Murakawa et al. (2005) who discussed that two linear polarization features found in their data may indicate the formation of an edge-on dust torus surrounding the carbon star.

Channel maps of the HCN transition in the $v=(0, 1^{1e}, 0)$ vividly show detailed features of expanding shells. The expansion velocities of the shells, traced with the HCN $J = 3 - 2$ transitions in the $v=0$ and $(0, 1^{1e}, 0)$ states are up to $\sim 13 \text{ km s}^{-1}$, which are close to the terminal velocity of $\sim 15 \text{ km s}^{-1}$ as observed from other molecular lines such as CS (Young et al. 2004), but are much larger than the that of the high energy HCN transition mentioned before. The expanding shells are found to be composed of many clumpy condensations.

The significant difference in distribution between HCN emission in $v=0$ and $(0, 1^{1e}, 0)$ states and the HCN emission in the $v=(1, 1^f, 0)$ state leads us to conclude that there are two discrete regions in the innermost CSE. One is a

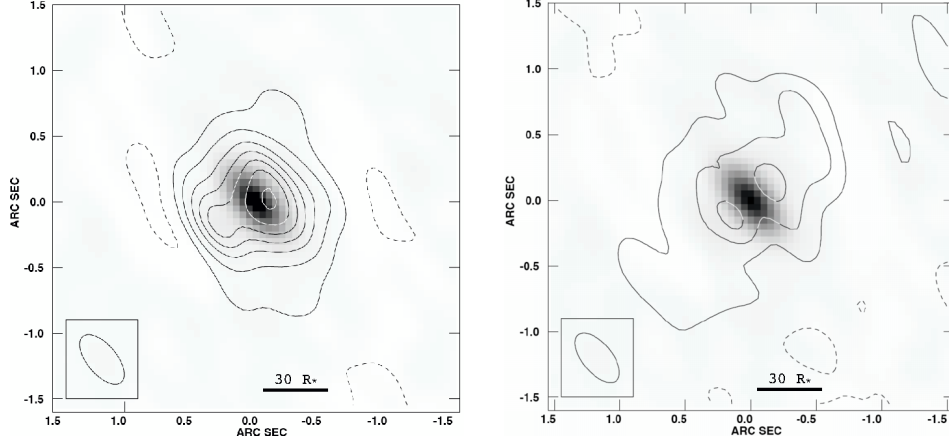


Figure 2. Total integrated intensity maps (contours) of HCN $J = 3 - 2$ $v = (0, 1^e, 0)$ (left) and $v = 0$ (right) states, overlaid on the continuum emission of the circumstellar dust and photosphere. For the $v = (0, 1^e, 0)$ state map, the contours are drawn at $-3, 3, 10, 20, 30, 40, 50$, and 60σ ($1\sigma = 57$ mJy), respectively. For the ground vibrational state map, the contours are drawn at $-3, 3, 6$, and 9σ ($1\sigma = 39$ mJy; Shinnaga et al. 2009).

region of radius less than $15 R_*$ where various molecular species have just formed and the gas has begun to be accelerated by stellar radiation. We name this region Region I. The other is a region outside of the Region I, Region II, where spectral lines indicate higher expansion velocity. These two discrete regions may have been created because the size distributions of the condensed dust particles are significantly different in these regions.

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